LCA Methodology

Predicted Environmental Impact and Expected Occurrence of Actual Environmental Impact

Part I: The Linear Nature of Environmental Impact from Emissions in Life-Cycle Assessment *(Int. J. LCA 3/1997)*
Part II: Spatial Differentiation in Life-Cycle Assessment via the Site-Dependent Characterisation of Environmental Impact from Emissions *(Int. J. LCA 4/1997)*

José Potting, Michael Hauschild

Process and Production Engineering, Dept. of Manufacturing Engineering, Technical University of Denmark, Building 403 II, DK-2800 Lyngby, Denmark

Corresponding author: José Potting

The Linear Nature of Environmental Impact from Emissions in Life-Cycle Assessment

Abstract

The necessity of the impact assessment phase in life-cycle assessment (LCA) is presently debated. The crux of the debate lies in the poor accordance in some LCA studies between the predicted environmental impact and the expected occurrence of actual environmental impact. That is in particular the case for impacts of a continental, regional and local character. We consider an impact assessment as being an indispensable phase of LCA, and see options for solving the identified problem. This article takes a closer look into the nature of the assessed impact in LCA in order to provide the basis for enhancement of life-cycle impact assessment. LCA is one of the analytical tools to support environmental policy focused on the control of present environmental problems. Nowadays, environmental problems are caused by concentration levels that result from the emissions of many sources together, rather than from single sources alone. The contribution from a single source is usually small or even marginal in comparison with the total contribution from all sources together. The multiple source character of the related impact categories provides the justification for the linear nature of the assessed impact in LCA. An article in the next issue of this journal will build further on this article, and will discuss the inclusion of temporal and spatial aspects (by a site-dependent approach) in order to enhance the accordance between the predicted environmental impact and the expected occurrence of actual environmental impact.

Keywords: Actual environmental impact; emissions, life-cycle impact assessment; environmental impact, multiple sources; environmental impact, predicted; environmental impact; life-cycle impact assessment; site-dependent approach, life-cycle impact assessment; spatial differentiation, life-cycle impact assessment

1 Introduction

The concept of life-cycle assessment (LCA) originates from energy analysis in the late sixties and early seventies. Later on, this analysis methodology is broadened to take into account resource requirements, waste production and emissions. In present LCA, the identification and quantification of energy and material consumption, and waste production and emissions (all together also referred to as environmental interventions), is covered by the inventory phase (CONSOLI et al., 1993; WEIDEMA, 1993).

It has only recently become common practice to interpret the environmental interventions from the inventory into their potential to contribute to environmental impact (CONSOLI et al., 1993; WEIDEMA, 1993). The classification and characterisation of the impact potential from the inventory data takes place in the impact assessment phase of LCA (CONSOLI et al., 1993; UDO DE HAES et al., 1996). There is an ongoing discussion as to whether an impact assessment should be a part of LCA. The crux of the debate lies in the limited accordance between the impact predicted by life-cycle impact assessment and the expected occurrence of actual impact. (DAALMANS, 1995; KLÖPFFER, 1996; PERRIMAN, 1995; WHITE et al., 1995).

The spotted lack of accordance seriously affects the credibility of LCA. It may cause the wrong products to be taken from the market or the wrong processes within the products life-cycle to be selected for improvement. Enhancement of the impact assessment phase is therefore of vital importance for the credibility of LCA.

The aim of this article is to come to a better understanding of the nature of the assessed impacts in LCA, and therewith provide the basis for enhancement of the impact assessment phase in LCA. An article in the next issue of this journal will discuss the inclusion of temporal and spatial aspects in LCA (by a site-dependent approach) in order to enhance the accordance between the predicted environmental impact and the expected occurrence of actual environmental impact.

Section 2 gives a brief overview of the debate about the necessity of the impact assessment phase in LCA. Some general features of the relationships between emissions and environmental impact are introduced in Section 3. Section 4 up to and including Section 7 describe the nature of the assessed impact within LCA. Section 8 draws some main conclusions, while Section 9 provides an outlook to the article in the next issue of the Journal of Life-Cycle Assessment.

2 Necessity of the Impact Assessment Phase

Many practitioners consider impact assessment to be a necessary part of LCA since the inventory data alone is usually not sufficient for environmental decision support. A long list of interventions is difficult to understand without explicit interpretation in relation to environmental problems and it is therefore often impossible to evaluate the results of life-cycle improvements based on an inventory alone (UDO DE HAES et al., 1996). Moreover, lack of an explicit impact assessment leads to an implicit one. Either the same weights are given to each intervention, or some interventions are qualitatively given more weight than others (JOLLIET et al., 1996; WENZEL et al., 1997).

Some additional arguments in favour of life-cycle impact assessment are given by KLÖPFFER (1996). His most obvious, and maybe the most important one refers to the definition of LCA as a tool which explicitly aims to address environmental impact (CONSOLI et al., 1993). Impact assessment is then of course an inevitable phase in LCA.

KLÖPFFER (1996) also summarises arguments in favour of restricting LCA to inventory analysis. Inventory methodology is fairly well developed, and energy and material flows can be established with high accuracy. The large uncertainties in the inventory of emissions (which are the basis of most life-cycle impact assessments), however, do not justify a subsequent impact assessment in which also new uncertainties are introduced. Furthermore, in contrast to impact assessment, a well performed inventory analysis can stand alone and may be used as such for improvements in some exceptional cases.

The main problem with life-cycle impact assessment consists in the absence of true relationships between interventions and environmental effects. The interventions established in the inventory analysis are expressed in amounts per functional unit and in principle, nothing is known about the source-strength and variation over time of the examined processes. Due to this lack of differentiation which is inherent to LCA, no environmental concentration can be predicted and, as a consequence, it does not seem possible to evaluate whether a no-effect level is surpassed. Therefore, there may be only little accordance between the impact predicted by life-cycle impact assessment and the expected occurrence of actual impact. Some clear examples of this are provided by SCHMIDT et al. (1996), GIEGRIECH (1996), POTTING and BLOK (1994 and 1995), OWEN and RHODES (1995).

Deliberating the pro's and con's, it is our opinion that LCA without an impact assessment phase is not an LCA. However, the credibility of the results from impact assessment may be seriously affected by the problems outlined above. We see options for solving this problem. Before sketching the direction that may be taken, however, it is necessary to present some general features of life-cycle impact assessment and discuss in more detail the cause/effect relationships between emissions and environmental impact. Based on this, the possibilities and limitations for an enhanced life-cycle impact assessment can be specified.

3 Cause/Effect Relationships between Emissions and Environmental Impact

A compound may have the intrinsic ability of bringing about one or more types of environmental impact. This intrinsic property depends on the specific physical, chemical and biological (toxicological) properties of the compound in relation to the properties needed to evoke the type of impact considered. A general model for the way in which this potential may lead to an actual impact is represented in Figure 1. If a compound does not have the relevant properties with regard to a specific impact category, it can be left aside. That is the type of decision which is made in classification.

The emission of a compound to the environment may have different forms. It can take place into the air, water or soil. The quantity of compound emitted will be something between very large and very small. This quantity can be emitted instantaneously, repeatedly with a certain frequency or continuously.

When emitted, a compound is distributed in the environment. The distribution can be restricted to one environmental compartment, although dependent on the properties of the compound and those of the specific environment, partitioning between compartments can also take place. Because of a dispersion within one compartment, most emissions will be diluted to some degree. In some cases, however, accumulation takes place because of bioaccumulation, or physical and chemical processes like sedimentation and deposition. The compound may be immobilised through irreversible binding or very strong adsorption. Furthermore, it may be removed from the environment to some extent by way of chemical or biological degradation.

The distribution processes that occur, are dependent on the properties of the compound, the emission characteristics and the characteristics of the compartment (air, water or soil) to which the emission takes place. As a result of distri-

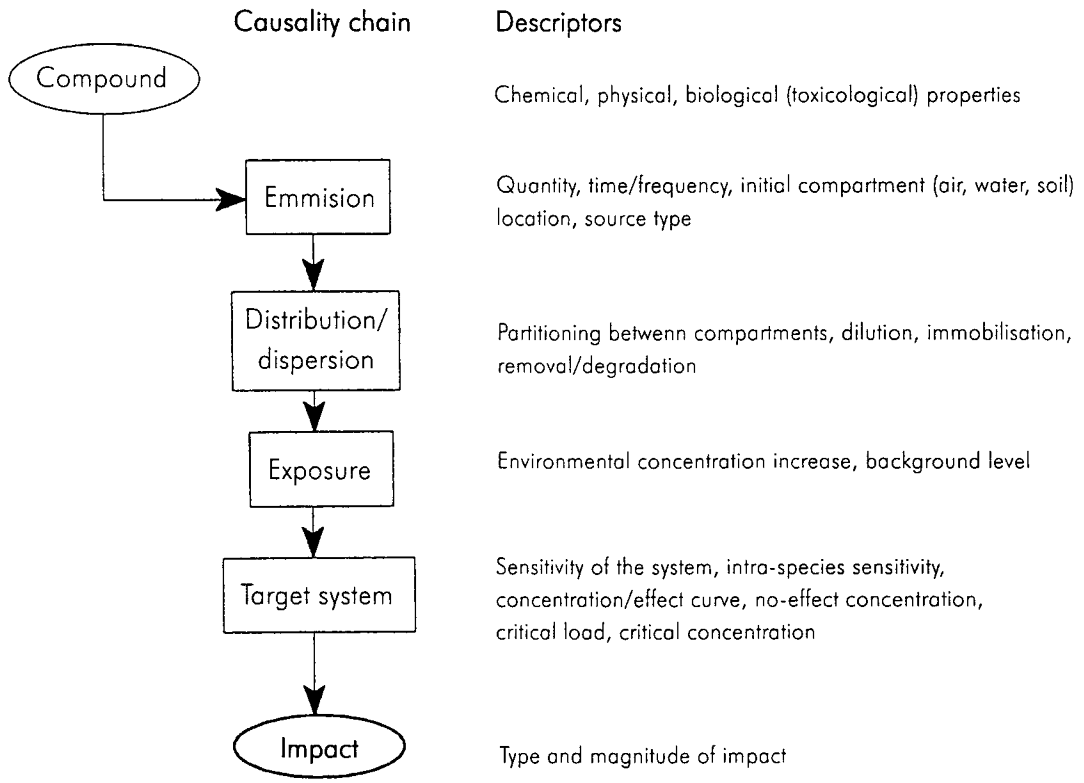

Fig. 1: General cause/effect chain for the environmental impact of an emitted compound (JAGER et al., 1994)

bution, there may be a certain amount of the compound at a specific time and specific place in the receiving environment. Some amount of the compound is often already present (background concentration), independent of the increasing concentration from the considered emission. The resulting environmental concentration is then the combined result of the concentration increase and the background concentration. When it is present in the receiving environment at the same time and place, a target system can be exposed to the compound (e.g. through surface contact, inhalation or ingestion).

The exposure to a compound may affect the target system. The occurrence of a particular type of environmental impact is dependent on the sensitivity of the target system, the intrinsic properties of the compound and the size of the exposure. For some impact categories (like the increased radiative forcing in global warming), the size of the impact is proportional to the size of the exposure. Most other impact categories (like toxicity or acidification) only occur when the size of the exposure exceeds a certain no-effect level.

The relation between the amount of compound emitted and the size of its environmental impact is the overall result of the relations within each link of the causality chain. In life-cycle impact assessment, the focus is mainly on this net result. It is the aim of characterisation to assess and quantify this net result from the inventory data (CONSOLI et al., 1993; FAVA et al., 1993; UDO DE HAES et al., 1996).

Characterisation should be based on knowledge about the environmental processes between emission and impact, and therefore take into account experience and knowledge developed in related scientific fields like environmental impact assessment (EIA) and hazard and risk assessment (RA) (CONSOLI et al.; 1993; FAVA et al., 1993). An important question regards the nature of the impact that can be assessed in LCA. This question is addressed in the following sections.

4 Predicted Impact and Expected Occurrence of Actual Impact

The interventions established in life-cycle inventory analysis are expressed in amounts per functional unit, and the source-strength and time-pattern of the examined processes are in principle unknown. Due to this lack of differentiation, the environmental concentration related to the entire product output from a process cannot be predicted. As a consequence, it does not seem possible to evaluate whether a no-effect level is surpassed. There may therefore be little accordance between the impact predicted by current life-cycle impact assessment and the expected occurrence of actual impact (WHITE et al., 1995).

The lack of accordance between predicted impact and the expected occurrence of actual impact was defended by HEIJUNGS et al. (1992) by stating that "...LCA is not concerned with the degree to which a NOEC is actually exceeded, but with the degree to which it is potentially filled up...". A foundation for this statement is given by UDO DE HAES et al. (1996), "...LCA is primarily a tool for resource conser-

vation and pollution prevention". For this reason "...all emissions are regarded as relevant on the basis of their intrinsic hazard characteristics, whether above or below the NOEC threshold..." (WHITE et al., 1995). This approach is known as the "less is better" approach within LCA circles.

As already mentioned in Section 1, the "less is better" approach is strongly debated, precisely because of the lack of accordance between predicted impact and the expected occurrence of actual impact. Therefore, some people believe that LCA should be restricted to inventory analysis, while others has come with suggestions for an enhanced impact assessment.

One of the most radical suggestions for an enhanced impact assessment is put forward by WHITE et al. (1995), and is known as the "above threshold" approach. The "above threshold" approach uses the inventory data to identify the processes with the largest emissions. For these emissions, concentration and related exposure levels, and surpassing of thresholds (like no-effect levels) are predicted with the help of additional site-information and tools like risk assessment and environmental impact assessment. The emission is taken into account only if a threshold is surpassed. An elaborated methodology according to this approach has been presented by HOGAN et al. (1996).

The usefulness of the "above threshold" approach is acknowledged and seen as being conceptually related by the SETAC-Europe Workgroup on Life-cycle Impact Assessment, but it also regarded as not being applicable within a regular LCA due to the extensive need of additional data that are generally not accessible. Besides practical limitations, the problem to link the exceeding of thresholds in a quantitative way to a functional unit is mentioned as a more fundamental reason for the inapplicability of this approach in LCA (UDO DE HAES et al., 1996; WHITE et al., 1995). We believe that the "above threshold" approach can provide important information additional to LCA, but that the value within regular LCA as such is indeed limited. At the same time, however, the complete disregard of thresholds as in the "less is better" approach is seen as not being justified and moreover unnecessary.

A third track is possible between both approaches. The explanation of this requires a short excursion into the history of environmental policy.

5 Product Oriented Environmental Policy

In the course of the sixties it became clear that the waste and emissions from our modern way of consumption and production lead to severe environmental problems. Since then, in most industrialised countries, an extensive environmental policy has been developed to bring the most urgent situations under control and to prevent similar situations in the future. Initially, the attention was primarily directed on regulating single activities on given locations (like factories). Environmental policy now covers an extensive body of policy instruments like licenses, levies and subsidies, and anti-pollution taxes. Location specific analytical tools like risk assessment and environmental impact assessment were developed to support decision-making by governmental bodies as well as by industry (NEPP, 1989; WENZEL et al., 1997).

This type of policy, also referred to as process oriented environmental policy, nowadays has a sound position in the industrialised countries with an advanced level of environmental policy and control. It has created a situation (1) in which risky local situations created by one single source are in principle prevented, and (2) where total emissions from all single sources together have on average been reduced substantially. Despite these remarkable changes, however, environmental problems have unfortunately not disappeared. Other environmental problems like acidification and ozone depletion have come into the picture (LANGEWEG et al., 1989; NEPP, 1989; WENZEL et al., 1997). These problems have a different nature than the ones in the local area of a single sources.

It has become evident that compounds with long residence times may be transported over fairly long distances before they arrive at the environment where they have their impact. Emission distribution and the related concentration and exposure increase in the receiving areas therefore have to be considered on a geographical scale larger than the local one in order to cover most of the impact from a single source. In addition, the dramatic increase of product manufacturing and consumption has resulted in a more disperse distribution of sources and subsequent dispersion of emissions (BERDOWSKI et al., 1995; LANGEWEG et al., 1989; NEPP, 1989; PPE, 1994; WENZEL et al., 1997).

Receiving areas related to single sources overlap largely. Nowadays, the concentration level in the receiving environment is the result from many sources together rather than from a single source alone. Actually, the contribution from a single source is usually small or even marginal in comparison with the total pollution level from all sources together. The process oriented environmental policy appears to be rather ineffective in curbing the environmental problems from concentration levels with such a multiple source character (PPE, 1994).

In the search for a more effective way to approach this issue, insight grew that all pollution can be traced back to the production, use and disposal of products. From this point of view, pollution prevention can be achieved in roughly two ways: (1) By stimulating environmental friendly products at the expense of less benign alternatives, (2) by optimising within the life-cycle of a specific product. Policy with this aim is referred to as product oriented environment policy. Several countries have started to develop such a policy (NEPP, 1989; PPE, 1994; WENZEL et al., 1997). LCA can be seen as one of the main analytical tools to support such decision-making.

6 Regional, Continental and Global Impact Categories

The previous section already gave account of the character of today's environmental problems: The concentration level in the receiving environment is nowadays the result from many sources together rather than from a single source alone. A single source has only a small or even marginal share in the full contribution from multiple sources. Furthermore, emission distribution and the related concentration and exposure increase in the receiving areas has to be considered on a geographical scale larger than the local one in order to cover most of the impact from a single source. The main impact categories of concern are tropospheric ozone creation, eutrophication, acidification, stratospheric ozone depletion, increased radiative forcing in global warming and toxicity from compounds with a long residence time.

The multiple source character of today's environmental pollution suggests that not any single source will be able to lift the concentration in the receiving environment by itself from a situation below the no-effect level to a situation where the no-effect level is surpassed and the emission leads to a strong increase of impact, or from there to a situation where the no-effect level is substantially exceeded and the emission hardly contributes any more to an increase of impact (see Line A in *Fig. 2*). Therefore, all emissions are relevant for pollution prevention, whether above or below a no-effect level. Nevertheless, a product oriented environmental policy would also preferably give higher priority to pollution prevention in problem areas (Section A III in *Fig. 2*) and potential problem areas (Section II of Line A in *Fig. 2*) than in non-problem areas (Section I of Line A in *Fig. 2*). LCA should therefore preferably provide sufficient information to allow such a differentiation. That is why thresholds cannot be fully disregarded in LCA.

Existing characterisation modelling in LCA impact assessment most often takes the form of equivalency assessment. In equivalency assessment, the emitted amount of a given compound is multiplied with a factor that relates this emission to the amount of a reference compound with an equivalent impact. Equivalency assessment assumes a linear relation between the amount of an emitted compound and its resulting impact.

In general, concentration levels (or better its resulting exposure or dose) are not linearly related to its resulting impact, but this relation will typically reflect a sigmoid curve. The impact size from a concentration increase is then given by the movement on the concentration/effect curve from the situation without, to the situation with an increased concentration. The impact size per unit of concentration increase may be put on a par with the slope of the concentration/effect curve and thus be taken as linear, as long as the concentration increase is marginal compared to the "background concentration". This holds true where the "background concentration", that is the situation without concentration increase, reflects the total environmental concentration from

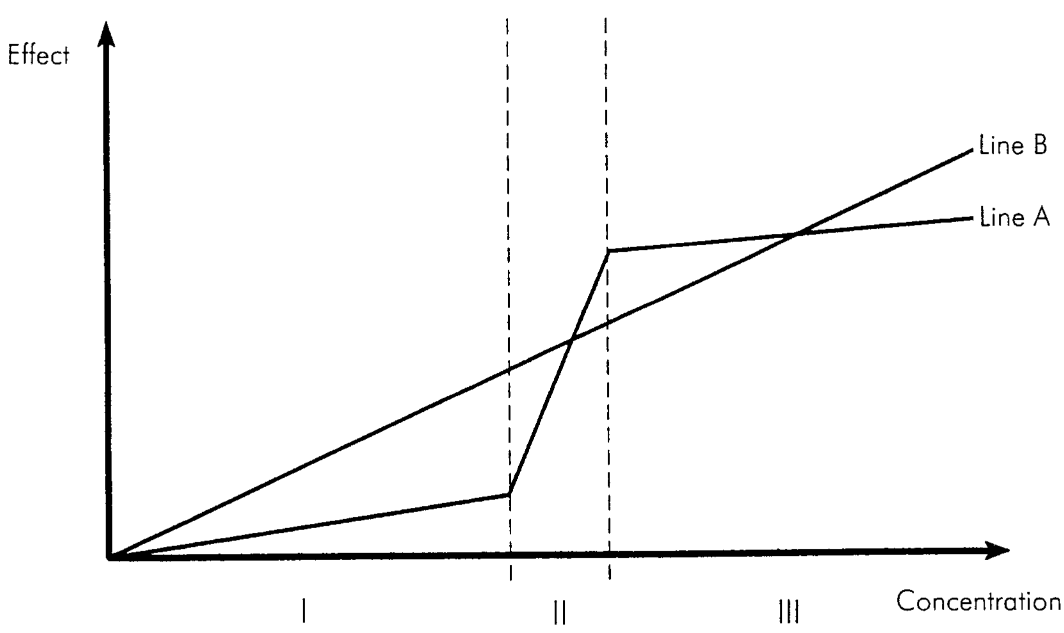

Fig. 2: Line A represents the shape of a regular concentration/effect curve in which three situations can be distinguished: (I) The environmental concentration section below the no-effect level, (II) the environmental concentration section at which the no-effect level is surpassed and where the emission leads to a strong increase of impact, and (III) the environmental concentration section where the no-effect level is substantially exceeded and the impact is so strong that the emission hardly contributes to any further increase. Line B represents the common situation in LCA practice where one linear relationship between emission and impact is assumed and thus for all problem situations the same proportionality or equivalency factor is used

many sources together to which the full emission of a single source only contributes marginally.

If the full emission from a single source can be regarded as marginal, the same inherently holds true for the emission related to one product unit.

7 Local Impact Categories

The multiple source character of today's environmental pollution, and the assumed marginality of the contribution from a single source holds on average true for impact categories of regional and higher scale. However, the situation is somewhat different for impact categories for which emission distribution has to be considered on a local scale in order to catch most of the impact from that single source. Here the emission from that single source often contributes considerably to the concentration level in the receiving environment and the source can therefore not be regarded as marginal.

It was local environmental problems that initiated the extensive body of process oriented environmental policy. For the purpose of impact assessment in LCA, it therefore seems fair to assume that environmental concentration levels resulting from one single source generally remains below the no-effect level (section I of Line A in *Fig. 2*) due to the process oriented policy measures. At least this is expected to be the case for the most developed countries. The first section of the sigmoid concentration/effect curve may defensibly be taken as linear. Therefore, the increase in local impact can be regarded as linear with the environmental concentration and exposure increase in the same way as for regional, continental and global impacts. However, there are three exceptions from this assumption of linearity for local impacts.

The first exception concerns the zone very closely surrounding the discharge point where an excess of the no-effect level (Section II and III of Line A in *Fig. 2*) may still occur. In environmental regulation, the exceeding of the no-effect level is accepted within a certain defined dilution zone. This zone is in general situated at, or immediately surrounding the domain of the releasing industry, and might thus be considered a part of the technosphere rather than the ecosphere. It can therefore be argued that LCA can disregard this exception from the marginality assumption in characterisation modelling.

The second exception from the assumption of linearity for local impacts concerns human and ecological exposure to toxic compounds at levels above the no-effect level. Such exposure may occur in situations where the background concentration is already close to or above the no-effect level and the additional contribution from an individual source leads to a shift from one problem situation to the next. That individual source, although contributing to local impact, can defensibly be regarded as contributing to a concentration level with a multiple source character as well. That is, because other sources are equally responsible for the shift from one problem situation to the other. Therefore, that individual source can be treated as connected to one problem situation alone (either Section II or III of Line A in *Fig. 2*).

The third situation where a no-effect level may be exceeded for human beings are the exposure of consumers during the products use stage and exposure of workers in processes of different life-cycle stages. Exposures related to these situations often have an acute character (relatively strong exposure of a short duration) and the occurrence of effects is highly dependent on the duration of the exposure. Exposures with an acute character are typical for the indoor and the working environment. It is questioned by LCA experts whether these exposures should be part of LCA. This issue is not yet thoroughly discussed and it therefore seems to be inappropriate to draw conclusions here. However, several methods are in the making to assess occupational health in a life-cycle framework (POTTING et al., 1997; WENZEL et al., 1997).

8 Conclusions

The lack of accordance that exists between the predicted environmental impacts by life-cycle impact assessment and the expected occurrence of actual impact seriously affects the credibility of LCA. It is our strong belief that these problems can be overcome as soon as we accept and have a clear understanding of the nature of the assessed impact in LCA in relation to the specific application domain of LCA: The effective controlling of environmental problems caused by concentration levels that are the result from many sources together rather than from single sources alone.

The impact from a concentration increase is given by the movement on the concentration/effect curve from the situation without, to the situation with increased concentration. The impact size per unit of concentration increase may be put on a par with the slope of the concentration/effect curve, and thus be taken as linear, as long as the concentration increase is marginal compared to the "background concentration". This holds true where the "background concentration", that is the situation without concentration increase, reflects the total environmental concentration from many sources together to which the full emission of a single source only contributes marginally. If the full emission from a single source can be regarded as marginal, the same inherently holds true for the emission related to one product unit.

The marginality assumption is expected to be justified for the non-local impact categories: Eutrophication, acidification, tropospheric ozone creation, stratospheric ozone depletion, increased radiative forcing in global warming and toxicity from compounds with a long residence time. For impact categories with a local character, the full emission from a single source may often contribute considerably to the concentration in the receiving environment. Here, the source can therefore not be regarded as marginal, but it seems fair to assume that the resulting environmental concentrations remain below the no-effect level (section I of

Line A in *Fig. 2*) due to the process oriented policy measures. The first section of the sigmoid concentration/effect curve may therefore defensibly be taken as linear.

9 Outlook

Current characterisation models always take the same proportionality for the relationship between the amount of compound emitted and its resulting impact. This single proportionality assumes the existence of one standard situation for each link in the cause/effect chain (→ *Fig. 1*). The concentration increase of a given compound, for instance, always leads to the same impact size, independent from its position on the concentration/effect curve. For all problem situations, the same proportionality (or equivalence factor) is used (Line B in *Fig. 2*).

The restriction to one standard environment may be relevant for impact categories of a global nature, but is an oversimplification for non-global impact categories (see also Section 3). For these impact categories, some more differentiation is necessary. A solution is expected in a site-dependent approach where it is assumed that the relevance of life-cycle impact assessment can be enhanced by the inclusion of a few site-parameters in the assessment process. An article in the next issue of the International Journal of Life Cycle Assessment will discuss the requested levels of detail in characterisation modelling in LCA, and next outline the site-dependent approach.

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